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Integrated Assessment of Soil Quality and Heavy Metal Contamination in Arid Agricultural Soils of Northwestern Uzbekistan

Mirkhaydarova Gulmira Sultanovna

Associate Professor of the Department of Agrochemistry and Soil Science, Tashkent State Agrarian University, Tashkent region, Uzbekistan

Ruzmetov Maksud Ismailovich

Professor, Institute of Soil Science and Agrochemical Research. Tashkent city, Uzbekistan

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Abstract: Soil contamination by toxic elements is one of the major environmental challenges affecting soil quality and ecosystem sustainability, particularly in arid regions. The accumulation of heavy metals in soils can disrupt nutrient cycling, reduce soil biological activity, and pose potential risks to agricultural productivity and human health. Therefore, assessing soil contamination and ecological condition is essential for sustainable land management. This study aimed to evaluate the ecological condition and soil quality of agricultural soils located in the Mehnatobod and Koklikol massifs of the Qoʻngʻirot district in the Republic of Karakalpakstan. The mechanical composition, agrochemical properties, salinity level, and heavy metal concentrations of soils were analyzed. In addition, SQI was calculated by integrating physicochemical soil indicators and ecological parameters into a single composite index. The results showed that the studied soils are characterized by relatively low humus content and limited nutrient availability. The analysis of chemical elements revealed that several metals exceeded permissible limits. In particular, arsenic (As) showed the highest contamination level, reaching values up to 40 times higher than the permissible limit. Chromium (Cr), nickel (Ni), and vanadium (V) concentrations exceeded permissible limits approximately twofold, while lead (Pb), cobalt (Co), and molybdenum (Mo) exceeded them by up to threefold. The calculated SQI values ranged from 49 to 55, indicating moderate soil quality levels. Although soil physicochemical properties were relatively stable, ecological indicators reduced the overall soil quality score. These findings highlight the importance of environmental monitoring and sustainable soil management practices to improve soil ecological conditions and maintain long-term agricultural productivity.

Keywords: Soil quality, Soil Quality Index (SQI), heavy metal contamination, agrochemical properties, soil ecological assessment, arsenic contamination, arid agroecosystems, environmental monitoring, sustainable soil management, Karakalpakstan soils.

Introduction: Soil is one of the most important natural resources that supports ecosystem stability, agricultural productivity, and environmental sustainability. It plays a crucial role in nutrient cycling, water regulation, and maintaining biodiversity in terrestrial ecosystems. Therefore, maintaining soil quality and ecological balance is essential for sustainable agricultural development and environmental protection [1].

In recent decades, soil degradation has become one of the most significant global environmental challenges. Processes such as salinization, erosion, nutrient depletion, and contamination by toxic elements significantly reduce soil fertility and negatively affect agroecosystem stability [2,3].

Among various soil degradation processes, heavy metal contamination has received increasing scientific attention due to its persistence, toxicity, and long-term ecological impacts. Heavy metals can enter soils through both natural geochemical processes and anthropogenic activities such as industrial emissions, mining operations, atmospheric deposition, irrigation with contaminated water, and the application of fertilizers and pesticides [4–6].

Once introduced into soil systems, heavy metals may accumulate in the soil matrix and persist for long periods. These elements can migrate through the soil–plant–water system and enter the food chain, potentially posing risks to both ecosystem stability and human health [7,8].

Numerous studies have demonstrated that elevated concentrations of heavy metals can negatively affect soil biological activity, microbial diversity, and enzymatic processes. These impacts may lead to disturbances in nutrient cycling and a decline in soil fertility [9,10].

Given the complexity of soil systems, evaluating soil ecological conditions requires integrated approaches that consider multiple physical, chemical, and biological indicators. In this context, the Soil Quality Index (SQI) has become one of the most widely used tools for assessing soil health and environmental sustainability [11–13].

The SQI approach integrates various soil indicators into a single quantitative value that reflects the functional status of soil systems. This integrated assessment method allows researchers to identify degradation processes, evaluate land management practices, and monitor environmental changes in agricultural landscapes [14–16].

Arid and semi-arid regions are particularly vulnerable to soil degradation due to harsh climatic conditions, low organic matter input, and intensive land use practices. In such environments, soil ecosystems are highly sensitive to anthropogenic disturbances and environmental stress factors [17,18].

Recent studies conducted in agricultural regions worldwide have shown that heavy metal accumulation may significantly reduce the ecological component of soil quality even when soil fertility indicators remain relatively stable [19,20].

Therefore, the aim of this study was to evaluate soil quality and heavy metal contamination in agricultural soils of northwestern Uzbekistan using the Soil Quality Index (SQI) approach.

Study Area Description

The study was conducted in the Qoʻngʻirot district located in the northwestern part of the Republic of Karakalpakstan, Uzbekistan. The district is one of the largest administrative units in the country, covering an area of approximately 74.49 thousand km². Geographically, it borders the Moʻynoq district in the northeast, the Boʻzatov district across the Amu Darya River in the east, the Qanlikoʻl and Shumanay districts in the southeast, the Dashoguz region of Turkmenistan in the south, and the Atyrau and Aktobe regions of Kazakhstan in the west and north.

Geographically, the study area is located approximately between 42°00′–44°30′ N latitude and 56°00′–59°30′ E longitude.

The relief of the study area is predominantly represented by the Ustyurt Plateau. The average elevation ranges from 150 to 200 m above sea level. The highest point of the district is the Karabovur ridge located in the western part of the territory, reaching approximately 290 m. The central part of the district includes the Barsa-Kelmes area, while the Qoraumbet saline plains are located in the eastern part and the Asakaovdon depression in the southern part. The territory bordering Turkmenistan also includes the Kaplonqir plain and the northern part of the Sarygamysh Lake.

The regional climate is sharply continental and arid. According to the Köppen–Geiger climate classification, the area belongs to the BWk type (cold desert climate). Summers are extremely hot and dry, whereas winters are relatively cold. The average annual precipitation is about 100 mm. The vegetation period lasts approximately 155–165 days and may extend up to 183 days in irrigated areas.

The soil cover is mainly represented by desert gray-brown soils. In irrigated agricultural areas, meadow-gray and meadow soils are widely distributed. In addition, saline and takyr soils are also common in the region, reflecting soil formation processes typical of desert environments.

METHODS

The research was conducted under both field and laboratory conditions. Laboratory analyses were performed using the following methods: mechanical composition was determined by the pipette method, humus content by the Tyurin method, total nitrogen by the Kjeldahl method, available phosphorus by the Machigin method, and exchangeable potassium by the photometric method. The concentrations of chemical elements in the soil were determined according to relevant GOST standards.

The ecological condition of the soils was assessed using the Soil Quality Index (SQI) method.

RESULTS AND DISCUSSION

General Characteristics and Agrochemical Properties of Soils

The mechanical composition, agrochemical properties, and salinity level of soils in the Mehnatobod and Koklikol massifs located in the Qoʻngʻirot district of the Republic of Karakalpakstan were investigated.

In the Mehnatobod massif, the plough layer of the soils is mainly characterized by a medium loamy texture, with the proportion of physical clay particles (<0.01 mm) reaching 32.6%. Along the soil profile, the mechanical composition varies between different horizons, where light loamy and sandy loam layers alternate with medium and heavy loamy textures in deeper horizons.

The humus content in the plough layer is 0.51%, indicating that these soils belong to the group of low-humus soils. A gradual decrease in humus content was observed along the soil profile, with values ranging between 0.32–0.48% in the lower horizons. The average total nitrogen content was 0.032%. The available phosphorus content in the plough layer reached 17.22 mg/kg, indicating a low level of phosphorus supply. The exchangeable potassium content was relatively high (273 mg/kg) in the plough layer and gradually decreased with soil depth.

The soils of the Mehnatobod massif are characterized by low salinity, with water-soluble salt content ranging between 0.105–0.165%. The salinity chemistry is mainly represented by a chloride–sulfate type.

In the Koklikol massif, the plough layer soils also exhibit a medium loamy texture, with the proportion of physical clay particles reaching 31.8%. Along the soil profile, the mechanical composition alternates between light loamy and sandy loam horizons.

The humus content in the plough layer is 0.509%, which also indicates a low humus supply. Along the soil profile, humus content varies between 0.28–0.48%. The total nitrogen content is approximately 0.05%. The available phosphorus content was 10.56 mg/kg, indicating a very low phosphorus supply. The exchangeable potassium content in the plough layer was 148 mg/kg and gradually decreased in deeper horizons.

The degree of soil salinity in the Koklikol massif is relatively higher than in the Mehnatobod massif. The content of water-soluble salts ranged between 0.155–0.305%. The plough layer soils are classified as moderately saline, while deeper horizons are slightly saline. Similar to the Mehnatobod massif, the salinity chemistry is dominated by the chloride–sulfate type.

Table 1

Main agrochemical properties of soils in the Mehnatobod and Koklikol massifs

Soil massif	Mechanical composition	Physical clay (<0.01 mm), %	Humus, %	Total N, %	Available P, mg/kg	Exchangeable K, mg/kg	Water-soluble salts, %	Salinity level	Salinity type
Mehnatobod	Medium loam	32.6	0.51	0.032	17.22	273	0.105–0.165	Low	Chloride–sulfate
Koklikol	Medium loam	31.8	0.509	0.05	10.56	148	0.155–0.305	Moderate	Chloride–sulfate

Soil Contamination with Chemical Elements

The concentrations of chemical elements were analyzed in soils of the Mehnatobod and Koklikol massifs located in the Qoʻngʻirot district of the Republic of Karakalpakstan. The results revealed the accumulation of several heavy metals and toxic elements in the soils of the study area.

The analytical results showed that the concentrations of beryllium (Be) and manganese (Mn) did not exceed the permissible limits. Similarly, the levels of zinc (Zn), copper (Cu), cadmium (Cd), antimony (Sb), and tin (Sn) remained within the acceptable threshold values, indicating a relatively low contamination level for these elements.

However, noticeable exceedances were detected for several elements. In particular, the concentrations of vanadium (V) and chromium (Cr) were approximately two times higher than the permissible limits. The concentration of nickel (Ni) also exceeded the regulatory standards in many soil samples and in some cases reached up to twice the permissible levels.

The contents of cobalt (Co) and molybdenum (Mo) were recorded at levels approximately three times higher than the established limits. In addition, elevated concentrations of lead (Pb) were detected in several samples, exceeding the permissible values.

The most significant contamination was observed for arsenic (As). In some soil samples, its concentration exceeded the permissible limits by several tens of times, with maximum values reaching up to 40-fold higher than the standard levels. This indicates a strong accumulation of toxic elements in the soils of the study area.

Overall, the results demonstrate that Cr, Ni, and V exceed the permissible limits by approximately twofold, while Pb, Co, and Mo exceed the limits by about threefold. Among the analyzed elements, arsenic (As) represents the most critical contaminant.

The accumulation of these elements in soils may enhance their migration through the atmosphere–soil–water–plant–animal–human system, potentially posing environmental risks to agroecosystem stability and human health.

Distribution of Heavy Metals and Environmental Assessment

The results of the study revealed a heterogeneous distribution of chemical elements in the soils of the Mehnatobod and Koklikol massifs located in the Qoʻngʻirot district. While some elements were found to be close to their natural geochemical background levels, others significantly exceeded the permissible limits, indicating varying degrees of soil contamination.

Based on the contamination levels, the analyzed elements were classified into three groups.

Group 1 — elements within permissible limits

The concentrations of Be, Mn, Zn, Cu, Cd, Sb, Sn, and Se did not exceed the permissible limits in the studied soils. These elements are characterized by relatively stable geochemical background levels in the soils of the study area, indicating a low level of anthropogenic influence.

Group 2 — moderately elevated elements

The concentrations of V, Cr, and Ni were found to be approximately two times higher than the permissible limits. This suggests the accumulation of heavy metals in soils under the influence of technogenic or geochemical processes, which may be associated with atmospheric deposition, irrigation water, or regional geochemical characteristics.

Group 3 — highly contaminating elements

The concentrations of Pb, Co, and Mo exceeded the permissible limits by up to three times. The highest contamination level was observed for arsenic (As). In several soil samples, the concentration of arsenic exceeded the permissible limits by up to 40 times, indicating a strong accumulation of toxic elements in the soils of the study area.

Such elevated concentrations indicate the potential accumulation of toxic elements in soils and highlight the possibility of their migration through agroecosystems along the trophic chain.

The obtained results are consistent with findings reported in previous studies. For example, Alloway (2013) emphasized that the accumulation of heavy metals in soils is frequently associated with industrial activities, irrigation water, and atmospheric emissions. According to this study, Cr, Ni, and Pb are commonly found at elevated concentrations in soils located near industrial zones.

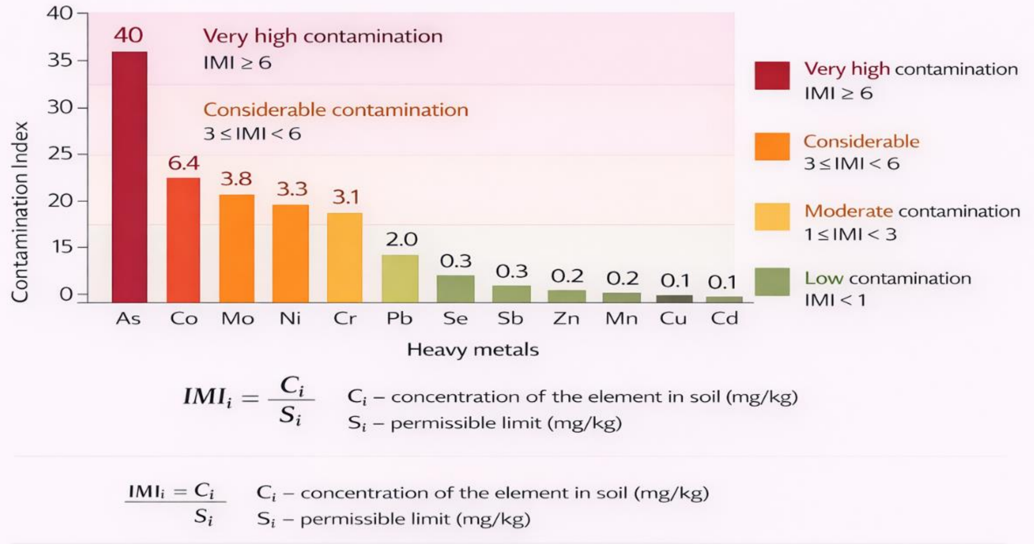
Similarly, Kabata-Pendias (2011) demonstrated that elevated concentrations of arsenic (As) and lead (Pb) in soils pose significant ecological risks, as these elements can enter the food chain through plant uptake.

Furthermore, research conducted by Zhang et al. (2018) in agricultural regions of China showed that increasing concentrations of Cr, Ni, and As in soils negatively affect agroecosystem stability and soil ecological functions.

In comparison with these studies, the heavy metal concentrations detected in the soils of the Qoʻngʻirot district correspond to the global trends of soil contamination. In particular, the elevated levels of arsenic (As) indicate the necessity of strengthening environmental monitoring and soil management practices in the region.

The accumulation of heavy metals in soils may lead to their migration through the atmosphere → soil → water → plant → animal → human system, forming a trophic transfer pathway. Such processes may reduce the quality of agricultural products, decrease crop productivity, and pose potential risks to human health and environmental sustainability.

Fig. 1. Comparative ranking of heavy metal contamination levels in soils based on the contamination index (IMI)



Interpretation of SQI Results. Soil Quality Index (SQI) Calculation Method. The soil quality of the study area was evaluated using the Soil Quality Index (SQI) approach, which integrates several soil indicators into a single quantitative index. This method allows a comprehensive assessment of soil conditions by combining soil physicochemical properties and ecological indicators.

The SQI was calculated using the following equation:

$$\mathrm{SQI} = \left(\frac{\sum_{i=1}^{n} S_i}{n} \right)$$

where:

S – quality score of an individual indicator

n – total number of selected indicators

In this study, soil quality assessment was based on two main groups of indicators:

- Soil property indicators (physical and chemical characteristics)
- Ecological condition indicators

Each parameter was normalized and assigned a score according to its contribution to soil functionality. The integrated SQI value was then calculated for each soil sampling site.

The results of the Soil Quality Index (SQI) assessment indicate that soils in the Qo‘ng‘irot district are characterized by moderate soil quality levels. In the Mehnatobod massif, the overall SQI values ranged between 49 and 55, with an average value of 52, indicating that the soils belong to the low to moderate quality classes. Although the soil property scores were relatively high (57–65), the ecological condition scores were lower (45–52), which reduced the overall SQI values.

A similar pattern was observed in the Koklikol massif, where the total SQI values ranged from 51 to 55, with an average value of 53. Soil property scores varied between 60 and 70, whereas ecological condition scores ranged between 44 and 51. These results suggest that despite relatively favorable soil physical and chemical properties, ecological factors negatively influence the overall soil quality in the study area.

The obtained SQI values are consistent with findings from several international studies on soil quality assessment. For example, Andrews et al. (2004) reported that agricultural soils with SQI values ranging between 50 and 70 are generally classified as having moderate soil quality. Similarly, Bünemann et al. (2018) emphasized that ecological stress factors such as heavy metal accumulation, salinity, and anthropogenic impacts may reduce the ecological component of soil quality even when soil fertility indicators remain relatively stable.

Furthermore, studies conducted by Mukherjee and Lal (2014) demonstrated that soils exposed to environmental pressures often show a discrepancy between soil fertility indicators and ecological condition indicators, which leads to moderate SQI values. The results obtained in the present study follow the same trend, indicating that environmental factors may play a significant role in shaping soil quality in the investigated region.

The relatively lower ecological condition scores observed in both massifs may be associated with environmental pressures such as heavy metal accumulation, soil salinization, and anthropogenic activities. These factors can influence soil biological activity, nutrient cycling, and overall ecosystem stability.

Therefore, improving soil ecological status through sustainable land management practices such as organic matter application, crop rotation, and environmental monitoring may contribute to increasing the overall SQI values of soils in the study area.

The SQI-based evaluation revealed that soils of the Mehnatobod and Koklikol massifs in the Qo'ng'irot district are generally characterized by moderate soil quality levels. Although soil property indicators demonstrate relatively favorable fertility conditions, ecological condition indicators are comparatively lower, which reduces the overall soil quality status.

The mechanical composition of the soils in the study area is predominantly medium loamy, which provides relatively favorable conditions for water retention and plant root development. Medium loamy soils are generally considered optimal for agricultural crops [10].

However, the relatively low humus content observed in the studied soils represents one of the major limiting factors affecting soil quality. Soil organic matter plays a key role in maintaining soil structure, nutrient cycling, and microbial activity [2,14].

The relatively low concentrations of available phosphorus and nitrogen indicate possible nutrient depletion processes associated with long-term agricultural use. Similar trends have been reported in agricultural landscapes of different regions [14,19].

Soil salinity is another environmental factor affecting soil quality in arid regions. Previous studies have shown that salinization remains one of the most significant land degradation processes affecting irrigated agricultural systems worldwide [15,18].

The results also revealed the accumulation of several potentially toxic trace elements in the studied soils. According to Alloway [4], heavy metals in soils may accumulate as a result of natural geochemical processes, irrigation water, and anthropogenic activities.

Recent international studies have also reported that elevated concentrations of elements such as chromium, nickel, and arsenic can negatively affect agroecosystem stability and pose potential risks to human health [10,19,20].

CONCLUSION

The present study evaluated the soil quality and heavy metal contamination of agricultural soils in the Mehnatobod and Koklikol massifs of the Qo'ng'irot district, Republic of Karakalpakstan. The results revealed that the studied soils are characterized by relatively low humus content and limited nutrient availability.

Analysis of chemical elements showed that several heavy metals exceeded permissible limits. In particular, arsenic (As) exhibited the highest contamination level, reaching up to 40 times higher than the permissible limit. Chromium (Cr), nickel (Ni), and vanadium (V) exceeded the permissible limits approximately twofold, while lead (Pb), cobalt (Co), and molybdenum (Mo) showed concentrations up to three times higher than the standard values.

The calculated Soil Quality Index (SQI) values ranged from 49 to 55, indicating moderate soil quality conditions. Although soil physicochemical properties were relatively stable, ecological indicators significantly reduced the overall soil quality level.

These findings suggest that environmental factors such as heavy metal accumulation and salinization may negatively influence soil ecological conditions in the study area. Therefore, strengthening environmental monitoring and implementing sustainable soil management practices, including organic matter application and improved land management strategies, are essential for maintaining soil health and long-term agricultural productivity.

The results provide a scientific basis for environmental monitoring and sustainable soil management in arid agricultural ecosystems.

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